

THIN FILM HEAT FLUX SENSOR FOR SPACE SHUTTLE MAIN ENGINE  
TURBINE ENVIRONMENTHerbert Will  
NASA Lewis Research Center  
Cleveland, Ohio 4413532-35  
11/2/81

The space shuttle main engine (SSME) turbine environment stresses engine components to their design limits and beyond. The extremely high temperatures and rapid temperature cycling can easily cause parts to fail if they are not properly designed. Thin film heat flux sensors can provide heat loading information with almost no disturbance of gas flows or of the blade. These sensors can provide steady-state and transient heat flux information.

Most heat flux sensors determine the heat flux by measuring the temperature on the top and bottom of a slab of insulating material. The heat flow per unit area through the insulating material is expressed as

$$\frac{H}{A} = \frac{K(T_1 - T_2)}{t}$$

where  $K$  is the coefficient of thermal conductivity,  $A$  is the area,  $t$  is the thickness,  $T_1$  is the temperature of one face, and  $T_2$  is the temperature of the other face.

In order to measure heat flux using the above equation, it is necessary to measure the temperature across an insulating layer. This is accomplished by putting a thermocouple on the top and bottom surfaces of the insulating layer. The two thermocouples are connected electrically so the voltages subtract. The subtracted output voltage is the difference between the two thermocouples. This difference voltage is then proportional to  $(T_1 - T_2)$ , which is the temperature difference across the insulating layer.

The above equation tells us that the thicker the insulating layer, the easier it is to measure the temperature difference across the layer. The heat flux encountered in an SSME environment can be several megawatts per square meter. For a 1- $\mu$ -thick aluminum oxide layer, it can be shown that a temperature difference of 0.17 K will be obtained for a heat flux of 1 MW/m<sup>2</sup>. This small temperature difference is difficult to measure with high-temperature thermocouples such as Pt-Pt13%Rh.

The thin film heat flux sensor described herein makes it easier to measure small temperature differences across very thin insulating layers. This is done by patterning 100 thermocouple sensors on the top surface and 100 sensors on the bottom surface of the insulating layer (refs. 1 and 2). A top and bottom thermocouple pair is connected through the insulating layer so the outputs subtract. The thermocouple pairs are connected in a thermopile arrangement so their difference voltages add. The resultant output voltage is proportional to the temperature difference across the insulating layer and is 100 times that of a single thermocouple pair.

[REDACTED]

A three-dimensional draw of a 10-thermocouple-pair heat flux sensor is shown in figure 1. The heat flux sensor consists of an insulating layer with 10 pairs of thermocouples on the top and bottom surfaces of the layer. The thermocouple pairs are sputter deposited onto the insulator surface in a circle. This configuration was chosen so that the sensor measures only the heat flux normal to the surface. The connecting wires are sputter deposited through holes in the insulator on the circumference of a larger diameter circle. This is done so the connecting wires do not disturb the heat flow in the vicinity of the thermocouple junctions.

The thin film heat flux sensor can be applied directly to the surface of engine parts. If the surface that the sensor is to be put on is electrically conducting, then an insulating layer must be applied first. All the layers are applied using RF diode sputtering. The thermocouples are patterned using photoresist lift-off and wet chemical etching techniques.

A previous presentation (refs. 1 and 2) on this subject indicated a problem with holes in the insulating layer between the sensor and the substrate. This problem has been solved by heating the substrate to 600 °C during the sputtering of an aluminum oxide insulating layer.

A thin film heat flux sensor fabricated on a silicon substrate is shown in figure 2. Although the sensor is not without problems, it did work when tested. The resistance of the sensor was 171 ohms across the terminals. The resistance between sensor and substrate was greater than 10 megohms, indicating no shorting through the insulator. The expected output of the gage as a function of heat flux is shown in figure 3. The measured output using a heat gun as a source of heat was 0.2 to 0.4 mV. This heat flux sensor failed after repeated temperature cycling. The failure was an open circuit in at least one of the thermocouple legs. Figure 4 shows a voltage contrast scanning electron micrograph of a failed thermocouple leg. It appears that the failure is at the plated through holes of the thermal barrier layer (see arrow in photograph).

So far all of the work on thin film heat flux gages has concentrated on flat substrates. SSME turbine blades are not flat. It is a problem to put a thin film pattern on the blade. The standard process of applying the thin film pattern is by sputter depositing a metal through a photoresist mask. When the photoresist mask is removed, the thin film pattern is left behind.

We are considering three methods for putting patterns on curved surfaces. In the first method, the pattern is produced on a flexible mask. Photoresist is applied to the curved surface. The mask is then held against the photoresist and the photoresist is exposed through the mask with ultraviolet light. The advantages of this method are that it is cheap and simple to implement. The disadvantage is that the mask cannot be accurately placed, which makes multilayered structures very difficult to fabricate. A variation of this method would be to use a flexible metal mask, and sputter deposit through the metal mask, eliminating the photoresist.

A second method under consideration makes use of a flat mask to put patterns on parts of the blade that are not highly curved, thus employing the same precision mask alignment equipment used for the flat samples. The advantage of this method is that it makes multilayered structures easier to

fabricate because of the precision alignment equipment. The disadvantages are that the pattern can only be applied to surfaces with a large radius of curvature, the light source must be highly collimated, and the alignment equipment is moderately expensive (\$5000 to \$50 000).

A third method makes use of a computer-controlled laser write pattern generator. A computer controls the writing of a small spot on the photoresist surface and also controls the X,Y,Z and tilt of the blade. The contour of the blade would have to be programmed into the computer ahead of time. By moving and tilting the blade, the pattern is written onto the blade. No mask is needed. An advantage of this method is that it is potentially very accurate and could be used to write patterns on highly curved surfaces. The disadvantages are that it would be very slow (it may take several hours to produce one pattern) and that this equipment can be very expensive (maybe \$1/2 to \$1 million).

#### REFERENCES

1. Will, H.: Thin Film Heat Flux Sensor: Electrochemical Society Proceedings, May 1990.
2. Will, H.: Thin Film Heat Flux Sensor: Advanced Earth-to-Orbit Propulsion Technology, Marshall Space Flight Center, May 1990.

# Thin Film Heat Flux Sensor With 10 Thermocouple Pairs

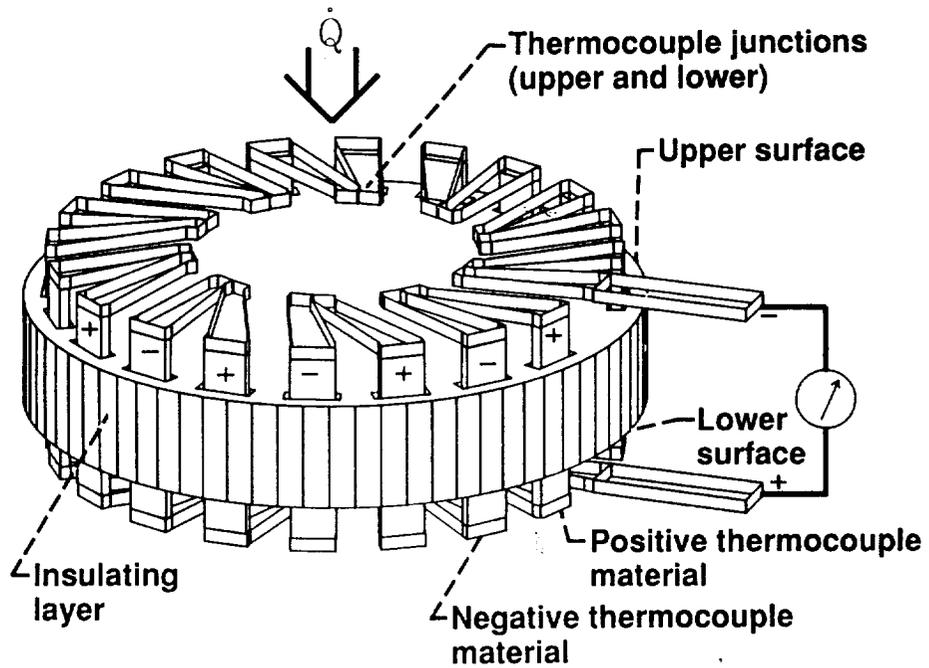


Figure 1

CD-91-52024

# Complete Thin Film Heat Flux Sensor

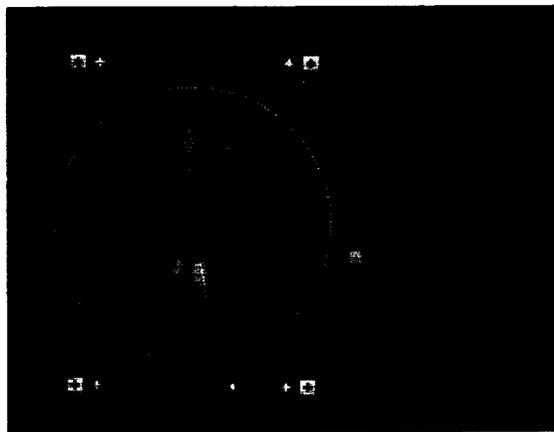


Figure 2

CD-91-52025

## Expected Output of Thin Film Heat Flux Gage as a Function of Heat Flux

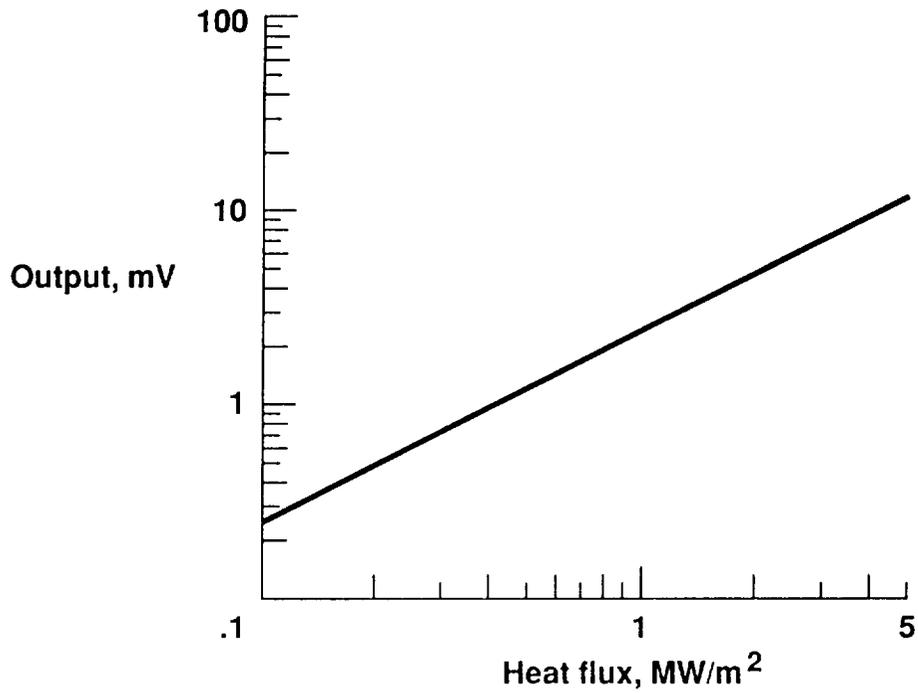


Figure 3

CD-91-52026

## Scanning Electron Micrograph of Failed Thermocouple Leg



ORIGINAL PAGE  
BLACK AND WHITE PHOTOGRAPH

Figure 4

CD-91-052027

